

# Model for Prediction Across Scales: A Multi-Resolution Approach to Climate System Modeling

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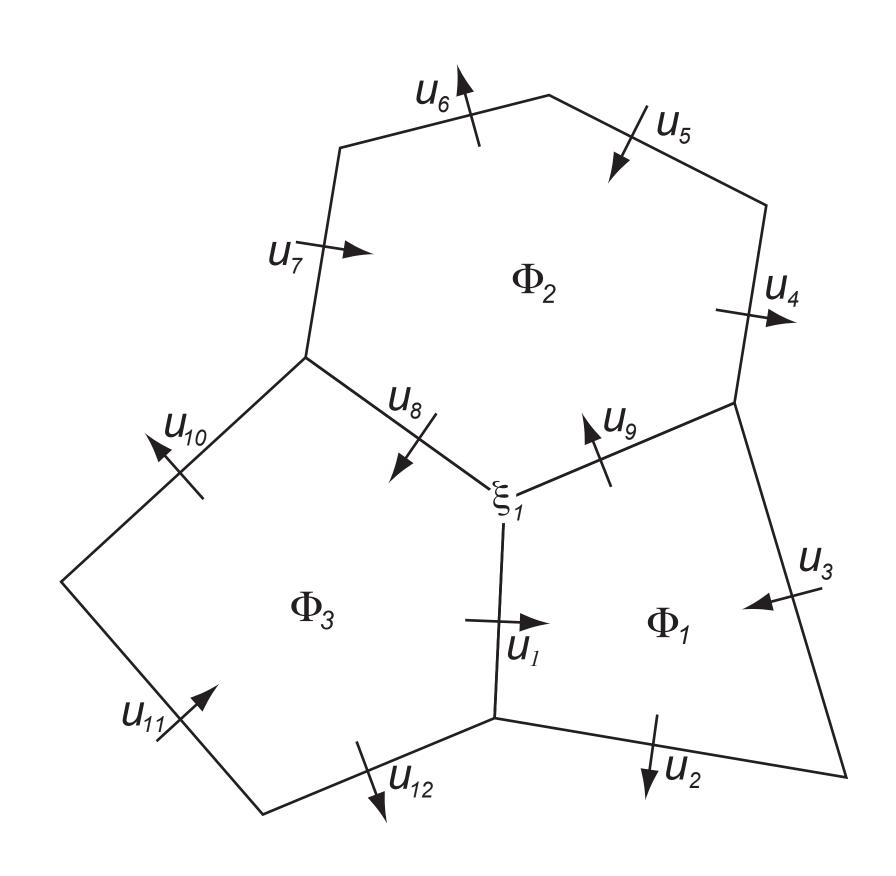
Office of Science

### Background and Motivation

This project is intended to produce climate system components that allow for multi-resolution simulation within the framework of global climate modeling.

The first defining feature of the project is the use of variable-resolution, Spherical Centroidal Voronoi Diagrams (SCVTs, see figures to far right). The development of SCVTs for climate applications is being led by Max Gunzburger, Lili Ju and Todd Ringler unde separate Office of Science funding. SCVTs are extremely easy to generate and produce high-quality, variable resolution meshes. See Ringler et al. (2008) and Ju et al. (2010).

SCVTs offer the possbility of placing enhanced resolution in certain geographical locations (such as over North America, Atlantic Ocean, Circumpolar Current, etc.) and thereby allowing for the regional simulation of climate-relevant processes that are to computationally intensive to be resolved in all locations all of the time.



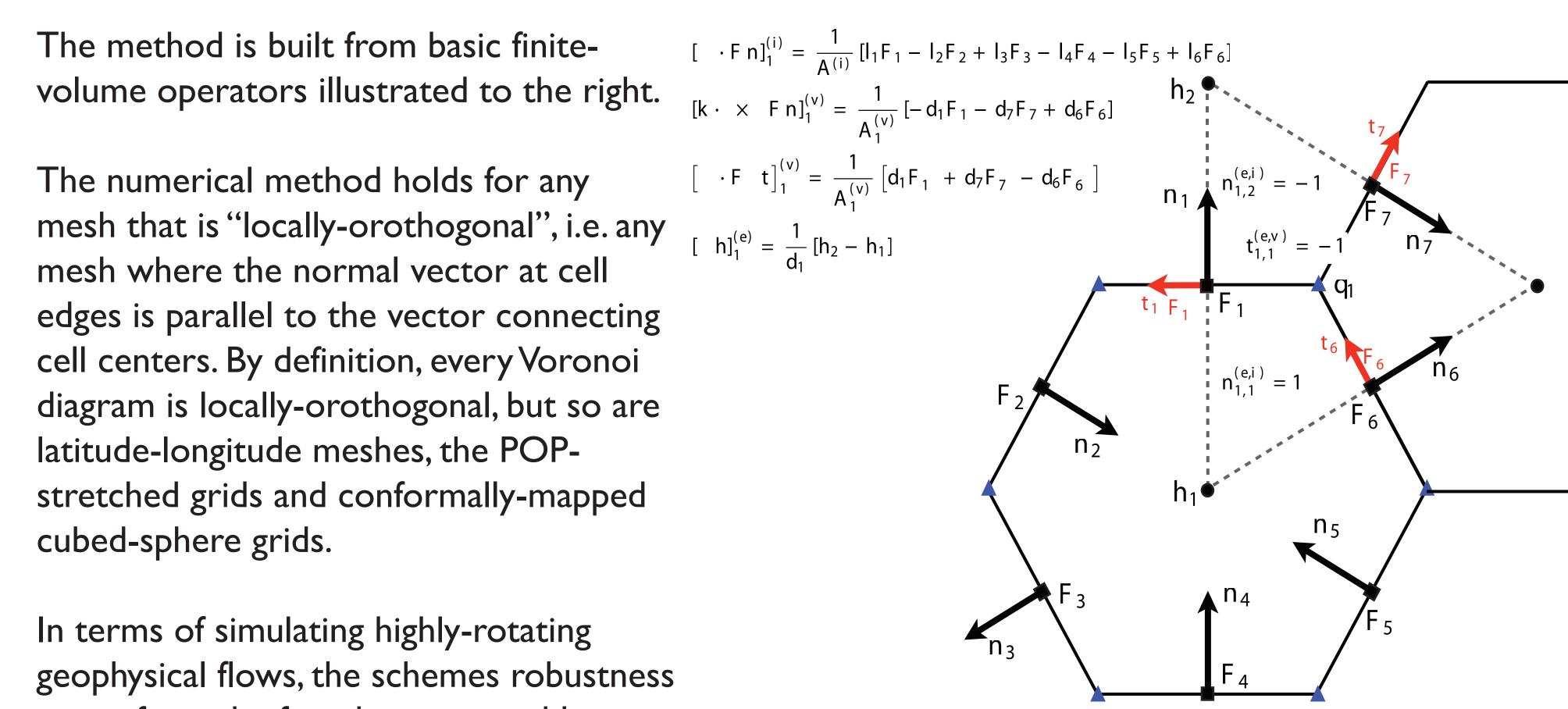
The second defining feature of this project is the creation of a "dynamical core" capable of robust simulation of geophysical fluid dynamics on variable resolution SCVTs. The figure to the left shows a part of a mesh composed polygons with four, five and six sides. The numerical scheme developed by Thuburn et al. (2009) and Ringler et al. (2010) conserves mass, total energy and potential vorticity on these variable-resolution meshes.

The numerical scheme employs a C-grid staggering where the normal components of velocity are retained at cell edges. Quantities such as mass, geopotential and kinetic energy are defined at cell centers. Quantities such as vorticity and potential vorticity are defined at cell edges.

The method is built from basic finite-

The numerical method holds for any mesh that is "locally-orothogonal", i.e. any  $[h]_1^{(e)} = \frac{1}{d_1}[h_2 - h_1]$ mesh where the normal vector at cell edges is parallel to the vector connecting cell centers. By definition, every Voronoi diagram is locally-orothogonal, but so are latitude-longitude meshes, the POPstretched grids and conformally-mapped cubed-sphere grids.

In terms of simulating highly-rotating geophysical flows, the schemes robustness stems from the fact that we are able to guarantee that the divergence on the dual (vorticity) grid is a convex interpolation of the divergences at the surrounding primary (mass) grid points.

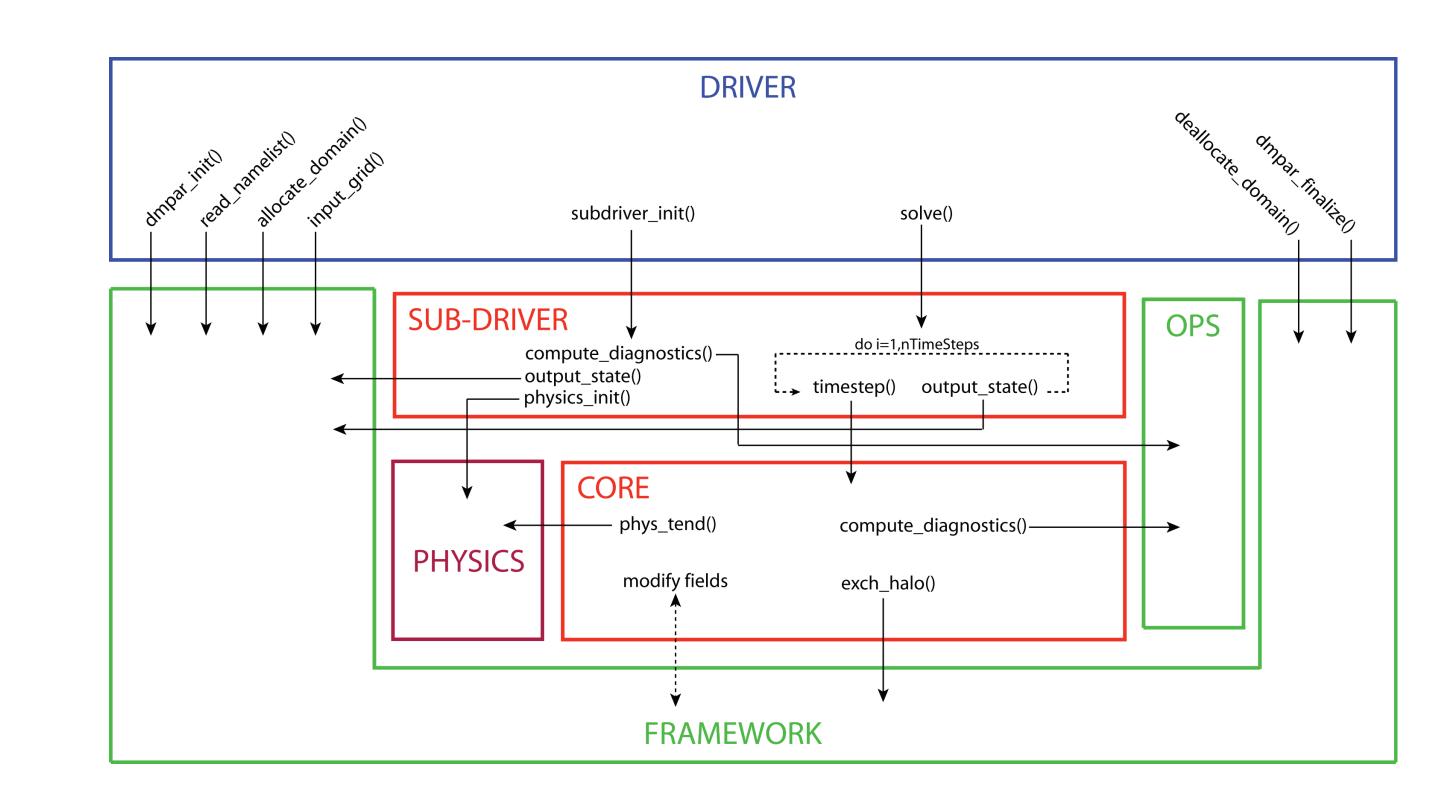


#### A Component-Independent Software Architecture

Since the notion of multi-resolution modeling is applicable to every component of a global Earth system model, we are striving to design a software framework that readily permits the extension of the modeling systems to a wide array of physical models.

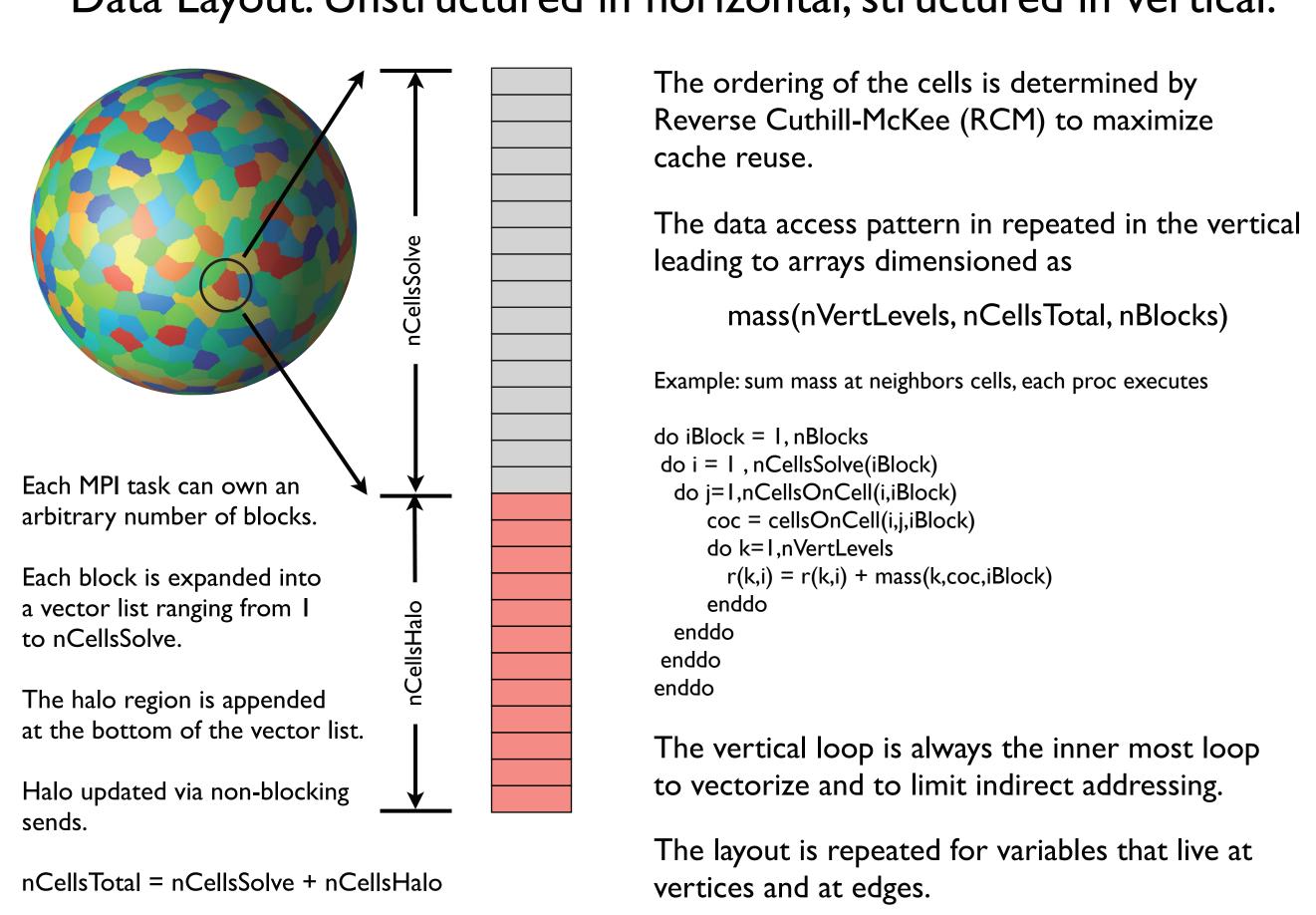
Each climate component model requires a very similar set of software support tools, such as parallel I/O, message-passing infrastructure for global reductions and halo updates and time management. We have grouped this functionality with a common "framework" architecture (see below). In addition, the framework includes derived data types and allocation/deallocation of framework-supplied data types through a component-independent registy system similar to (and an extension from) what is currently used in the NCAR Weather Research and Forecast (WRF) model.

The DRIVER and FRAMEWORK are component-independent. Within a given component (for example, the atmosphere) a common SUBDRIVER and PHYSICS module can be shared across various dynamical cores. This software architecture is designed to optimize the prototyping of single model components and is not intended to "couple" various model components.



The ability to support many types of meshes across, potentially, multiple components of a global climate model stems in large part from the very general, unstructured layout of the model data fields. Climate system components typically assume structured meshes and build this strucutre into the model software. This can lead to improved computational performance, but reduces the generality of the model formulation. No regular, data-access patterns are assumed in horizontal directions in the MPAS system. We mitigate the computational burden incurred from in-direct addressing in the horizontal by assuming a structure (direct-access) pattern in the vertical. We have demonstrated linear scaling out to several thousand processors. We intend to utilize heteorgeneous architectures (i.e. CPU/GPU systems) to accelerate the computational performance within the vertical "DO" loops.

Data Layout: Unstructured in horizontal, structured in vertical.



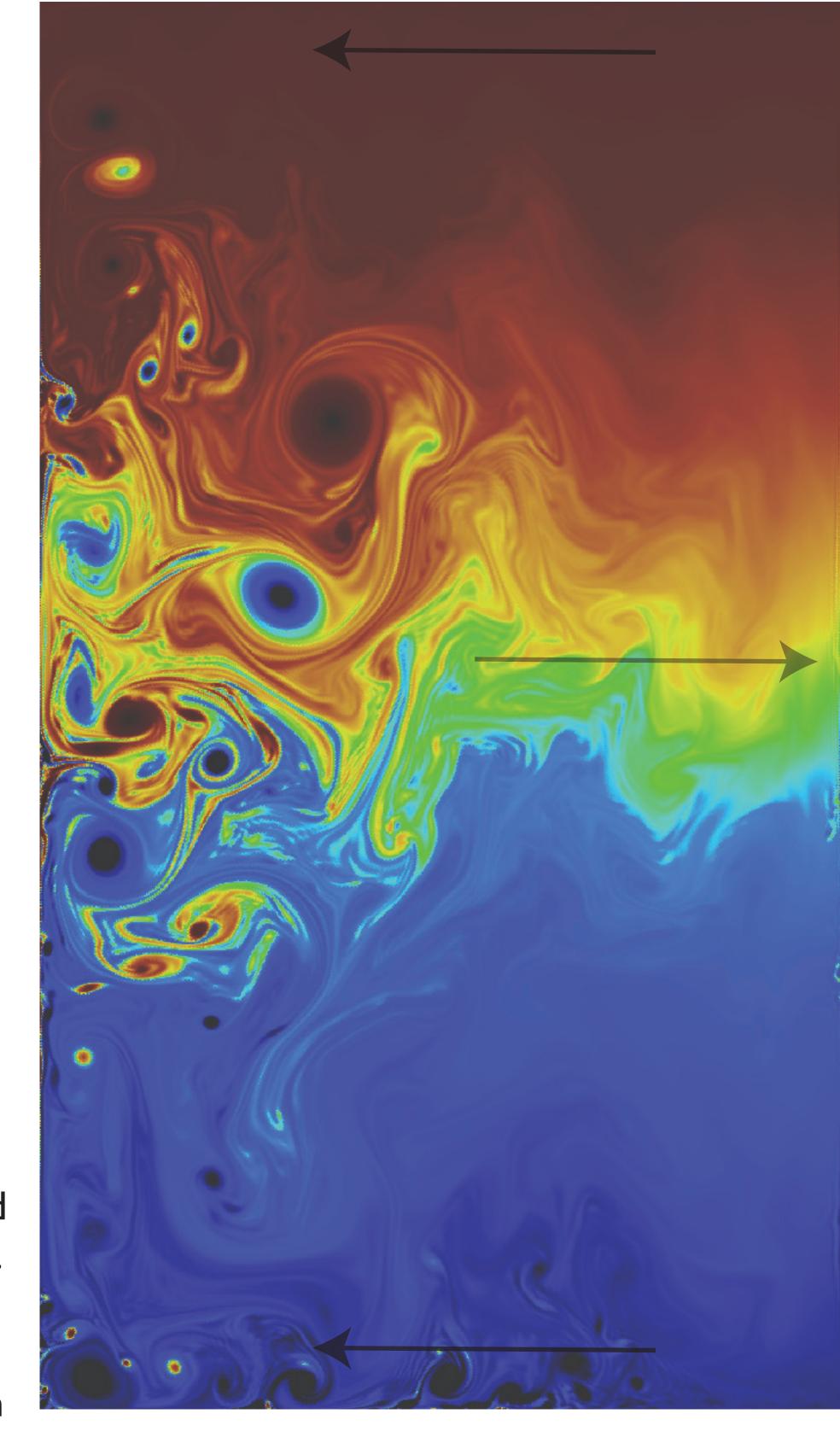
## Building Climate Model Components

The MPAS system currently supports three "cores": an ocean model, a atmsophere model and a shallow-water model. The LANL team has the lead responsibility for the development of the ocean model, whereas the NCAR team has the lead responsibility for the development of the atmosphere model. Given the integrated nature of the development environment, modeling improvements are rapidly leveraged across model components.

The LANL team is currently "porting" the Parallel Ocean Program (POP) into the MPAS system. Since the MPAS system supports the POP streched grids, we expect the MPAS version of POP to be largely backward compatible with the POP v2.0. To the right is a snapshot of potential vorticity taken from an idealized ocean basin simulation. PV is conserved to machineprecision and potential enstrophy is dissipated through the Sadourny anticipated-PV method.

The NCAR team has already produced a global, hydrostatic atmosphere model within the MPAS system. The figure below shows the relative vorticity field at day 16 of the Jablonowski and Williamson baroclinic eddy test case on a global 30 km mesh.

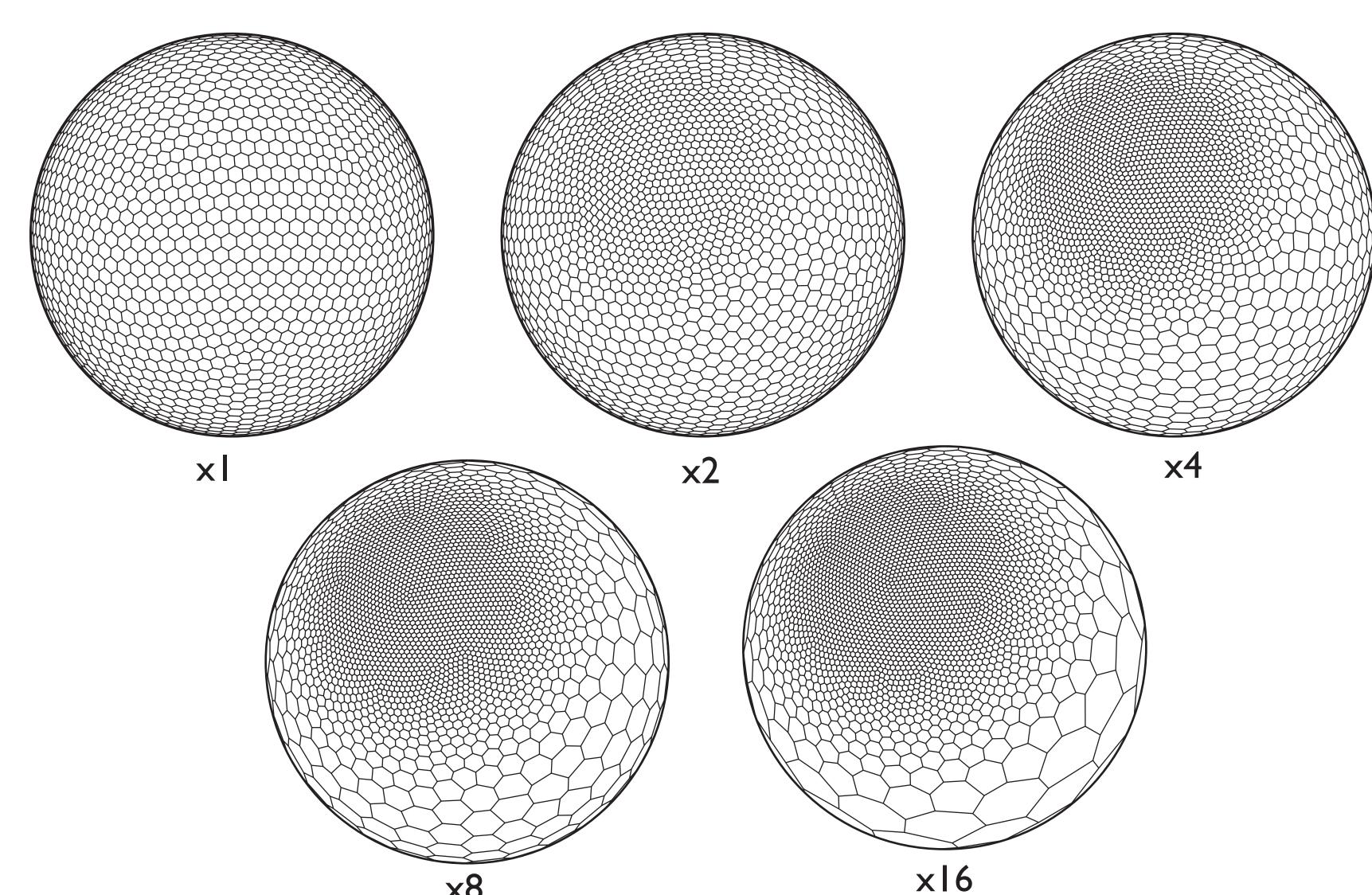
Under seperate funding and in cooperation with LLNL, this global hydrostatic model is being added to the CCSM system as an option for the Community Atmosphere Model (CAM).



Total PV in an idealized double-gyre system. Westward wind stress forcing along top and bottom and eastward wind stress forcing through the middle of the domain.

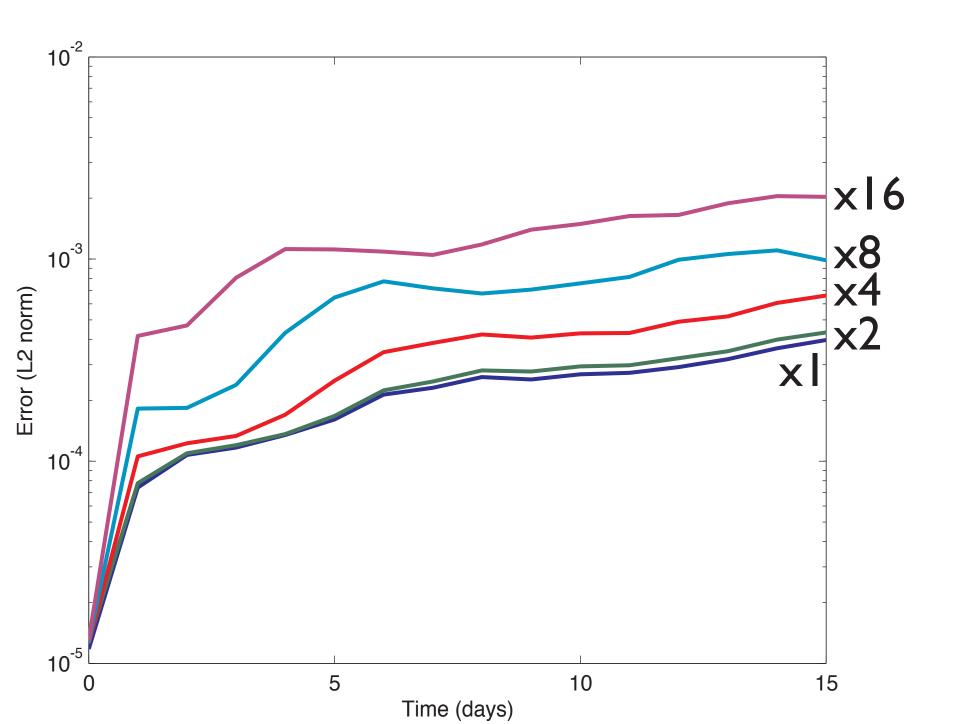
Global hydrostatic atmosphere model Day 16 of Jablonowski and Williamson test case Relative vorticity shown

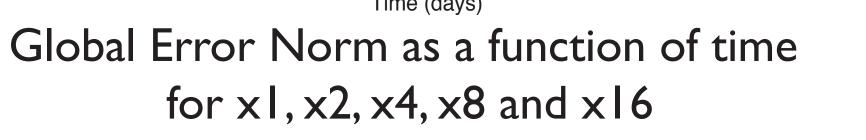
# Preliminary Results in the Shallow-Water System (in collaboration with Doug Jacobsen and Max Gunzburger at Florida State University)

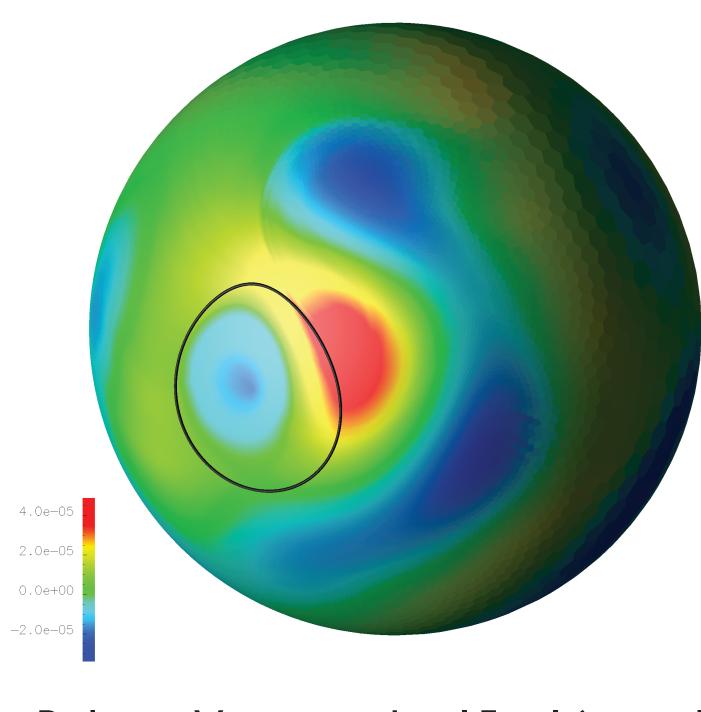


We have just begun to explore the variable-resolution capability of the MPAS system within the shallow-water equations. For this first experiment, we have taken the standard 40962 mesh and distributed the nodes with different factors of local mesh refinement around the orographic feature of shallow-water test case 5. Low-resolution versions of these meshes are shown above and are referred to as x1, x2, x4, x8 and x16 where, for example, the x16 has nominal grid spacing 16 times smaller in the vicinity of the mountain than in the far-field.

The error norms for the x1, x2, x4, x8 and x16 simulations are shown below. Also shown is the relative vorticity field for the  $\times 16$  simulation at day 15. Due to the coarsing of the far-field mesh, the error norms increase slightly with increasing focus of resolution around the topography. Even in the x 16 simulation, the vorticity field remains smooth throughout the experiment. All of the simulations conserve mass and PV to within machine precision and total energy to within time-truncation error. No dissipation is used or needed to maintain numerical stability.







Relative Vorticity, day 15, x16 simulation

#### References

Ju, L., T. Ringler and M. Gunzburber, 2010, Voronoi Diagrams and Application in Climate and Global Modeling, Numerical Techniques for Global Atmospheric Models, Lecture Notes in Computational Science, draft.

Ringler, T., L. Ju and M. Gunzburger, 2008, A multiresolution method for climate system modeling: application of spherical centroidal Voronoi tessellations, Ocean Dynamics, 58 (5-6), 475-498. doi:10.1007/s10236-008-0157-2

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